Renewable and Sustainable Energy Reviews 26 (2013) 761–768

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Assessment of optimal biofuel supply chain planning in Iran: Technical, economic, and agricultural perspectives

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ARTICLE INFO

Article history:
Received 1 December 2012
Received in revised form
17 June 2013
Accepted 24 June 2013
Available online 15 July 2013

Keywords:
Bioethanol
Supply chain model
ETBE
Optimal pathway
Iran

ABSTRACT

Contribution to satisfying the final energy demand, the necessities arises from waste minimization, and rural area's developments are the main incentives for biofuel usage in the Iranian energy supply system. This paper develops a model for the supply chain of bioethanol and bioETBE from the farms to the end users which integrates the temporal and spatial scales. It considers the techno-economical evaluations of first and second generation biofuels. The results provide practical insights for decision makers to introduce the biofuel into the Iranian energy systems. Here, the optimal designs of transition pathways of biofuel supply chain are available which successfully assesses the benefits and barriers to the decision maker.

Contents

1. Introduction

Sustainable and secure energy supply system for the future are of great importance to decision makers, researchers, and industry. Biofuels have been clearly emerged as a promising alternative in recent years. Europe will be able to produce biofuel more than 10 percent of gasoline and diesel demand by 2020 [1]. Several studies have reviewed the potential of biofuels [2,3]. Kim and Dale estimated the global potential production of 491 GL of bioethanol from wasted crops and crop residues which may be replaced with 32 percent of total gasoline consumption [4]. In addition, 458 TW h of electricity and 2.6 EJ of steam may be generated from the lignin-based residue of the production process. The main usage of ethanol is as an oxygenated fuel additive. However, it is mixed with gasoline and provides several advantages [5]. Taken into account different activities in the production of biofuels, their supply chain models in different countries and regions have recently received attention [6–10]. Akgul et al. have developed a corn-based bioethanol supply chain minimizing the total cost [11]. Roy et al. evaluated the life cycle of bioethanol production from rice straw in Japan [12]. Zhang et al. design an efficient switch grass-based supply chain for production of bioethanol [13]. They minimized the cost of the system on North Dakota state in the United States [13]. Akgul et al. proposed a supply chain model for

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http://dx.doi.org/10.1016/j.rser.2013.06.028

Nomenclature

List of symbols

$Al_{tie\tau}$	Land area of technology type τ for energy carrier e in region i, ha
$Al_{\max,tie\tau}$	maximum land available to be utilized
$co_{ltie\tau}$	operating cost per flow of energy carrier e from technology τ in region i at time t in level l
$cc_{ltie\tau}$	capital cost of technology type τ for energy carrier e in region i at time t in level l
$CF_{tie\tau}$	land capacity production, t/ha
$Dl_{tie\tau}$	average land degradation factor in time t and region i for energy carrier e and technology type τ
h	harvest residue generation fraction
hr	harvest residue recoverability fraction
HI	harvest index
X_{ltie}	flow in level l at time t in region i for carrier e
$OC_{lt\tau}$	operating cost of technology type τ in level l at time t
$CC_{lt\tau}$	capital cost of technology type τ in level l at time t
$pc_{tie\tau}$	potential of cultivation for energy carrier e in region i for technology type τ
r	discount rate
Y	capacity

Greek symbols

η	technology efficiency in each level
τ	subscript for technology type τ

Subscripts

A	level of end products
B	level of distribution
C	level of conversion
D	level of transport
e	subscript for energy carrier
E	level of supply systems
F	level of resources
HC	historical capacity
i,j,k	subscript for region
l	subscript for level
lt	life time of each technology
t	time horizon $t=1,\ldots,T$.
up	upper bound on variables
yr	time point

first and second generation biofuels in the UK [14]. Amigun et al. perform a prefeasibility analysis to evaluate the feedstock and technology options to produce bioethanol in South Africa [15]. They show the economic challenges for ethanol producers in South Africa. However, further economic analysis is required for simultaneous variations in parameters [15]. Corsano et al. propose a Mixed Integer Nonlinear Programming (MINLP) for the design of the sugar/ethanol plant [16]. Giarola et al. propose an optimization model for the future Italian biomass-based ethanol production from corn grain and stover [17].

These models may be categorized by their objective function, spatial dimensions, the biomass feed stocks, time horizons, etc. The literature regarding biofuel supply chains is restricted on particular aspects of the supply chain. In addition, no work has been adapted to consider the relevant concerns in Iran.

Currently agricultural wastes are not used for energy production in Iran. The increasing demand of the gasoline in recent years causes some challenges in energy supply system. The government made legislations about the fuel's quota for each vehicle. Thus, there is a need to the efforts toward the sustainable energy systems such that the fuel demand of the country is satisfied. In this context, biofuels are very interesting options. Moreover, they will improve the production of fuel additives in Iran. They provide opportunities for the waste minimization and create job opportunities especially in rural areas. Finally, their development will protect fossil fuel resources. These motivations will guide us toward developing a tool in order to evaluate the biomass potential to produce biofuels in Iran.

Previously, Najafi et al. [18] reported the annual potential of 4.91 GL of bioethanol in Iran. They found wheat, sugar cane bagasse, rice, barley, and corn as the most attractive crops [18]. According to Ghobadian et al., the potential of bioenergy is less studied in Iran in comparison to other renewable energy resources [19]. Taleghan site will only provide the energy for hydrogen usage. On the other side, applying the biofuels improves the waste minimization in Iran. Hamzeh et al. [20] have estimated the bioenergy potential of the country as 8.78×10^6, 7.7×10^6, and 3×10^6 t from agriculture, animal, and municipal wastes, respectively. Ghobadian [21] also predicts that bioethanol and biodiesel may sufficiently carry out the demand of E10 and B10 by 2026.

Since different aspects are involved in the introduction of biofuels in an energy system, a comprehensive supply chain model should be developed. Recently, Avami [22] presented a supply chain model to evaluate the potential of applying biodiesel in Iranian energy systems. Taking into the account the problem complexities and the needs of applying the current potentials, the present work has been conducted. In this work, the supply chain model adopted to consider the issues of bioethanol production in Iran. The main biomass feedstocks to produce bioethanol are the wastes, the crops residues and energy crops which are not completely concluded in the previous studies. This paper assesses the most important supporting plans to regionally introduce bioethanol and bioETBE in Iran for the next 28 years. The main concepts and equations are explained in Section 2. To solve different problems, several scenarios are considered in which the results are presented in Section 3. The results are analyzed and the implications are introduced to the policies. Section 4 concludes the paper with a short summary.

2. Model characteristics

This section introduces the main concepts of the current supply chain model as the basics are previously described by Avami [22]. The regional model, as depicted in Fig. 1, consists of different levels: resources, supply system, transport, conversion, distribution, and end-products. Thus, it enables us to encompass the variety of biomass feedstocks, conversion technologies, geographical diversity, and economics. It analyzes the most critical issues in the supply side of the bioethanol supply chain management and provides the optimal economic pathway over the temporal scale regarding the technical and geographical constraints.

Biomass to potentially produce bioethanol is classified as sugar-based, starch-based, and lingocellulosic feed stocks. The largest potential producer of bioethanol is Asia in which rice straw, wheat straw, and corn stover are the most important feedstocks [4]. Wheat straw and corn stover are the main potential feedstock in Europe (the second largest candidate) and North America, respectively [4]. The major feedstock in Brazil, the largest producer of

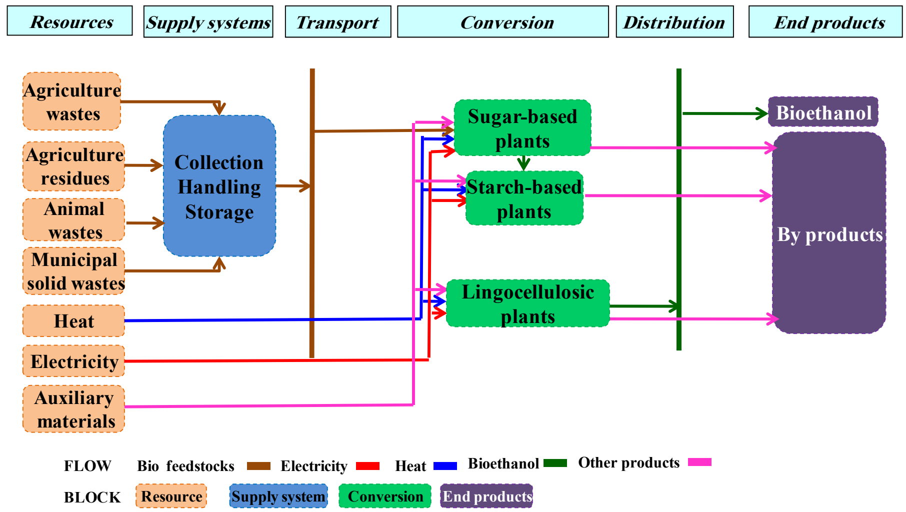

Fig. 1. Bioethanol reference energy system in Iran.

ethanol, is sugarcane. Different biomass is available in Iran in order to produce bioethanol. However, the cellose and hemicellose (carbohydrate's) content, the harvest potential and their capacities, and the available land may vary from region to region. Previously, Najafi et al. [18] evaluated the bioethanol production from different biomass wastes such as wheat, sugar cane, rice, barley, corn, potato, date, sugar beet, grape, and apple. In this work, biomass wastes from wheat, rice, barley, corn, potato, and date are considered as starch-based biomass and sugar cane and sugar beet are considered as sugar-based biomass. Rice straw, wheat straw, corn stover, barley straw, and bagasse as well as bioenergy crops (sweet sorghum, miscanthus, switchgrass) are available as lingocellulosic biomass. The potential of bioethanol from other resources is low [18] and is not involved in this study. The composition of biomass and the fraction of crop residues and wastes are taken from [4] and [18]. The biofuel production depends on the type of technology to harvest, collect, and process. These parameters are considered in supply system level. The available biomass from wastes and residues are converted to bioethanol within three different technological paths depending on the sugar-based, starch-based, or lingocellulosic nature of their feed streams. The bioethanol from production plant is sent to the distribution network to satisfy the demand in different geographical regions. As a whole, the technical aspects, as well as agricultural concerns determine the optimal economic supply chain involving plants, capacities, farm lands, the distribution capacities, and the biomass/fuel flows. The general mathematical formulation is similar to the work of Avami [22]. The previous model is adapted to produce bioethanol in which all bioethanol technologies are introduced to the model. Also the new model is capable to capture different feedstocks to produce bioethanol. It is here represented for the BioEthanol Supply Model (BETSM) as follows

$$\text{Minimize} \sum_{t=1}^{T}\sum_{l}\sum_{\tau}\left[\frac{OC_{lt\tau}}{(1+r)^{t}}+\frac{CC_{lt\tau}}{(1+r)^{t}}\right]$$

s. t.

Resource level :

$$X_{Ftie}=\sum_{\tau_F=1}^{k} CF_{tie\tau}.pc_{tie\tau}.Al_{tie\tau}, \tag{1}$$

$$Al_{tie\tau}\le\sum_{e}\sum_{\tau} pc_{tie\tau}.Al_{\max,tie\tau}-\sum_{yr=t-rp}^{t} Al_{yrie\tau}, \tag{2}$$

Supply level

$$X_{Etie\tau}=X_{Ftie\tau}.\,\eta_{Etie\tau}, \quad \text{for } e=\text{harvest residue} \tag{3}$$

$$\eta_{Etie\tau}=h_{tie}\times\ hr_{tie}, \tag{4}$$

$$h_{tie}=\frac{1}{HI_{tie}}-1, \tag{5}$$

$$X_{Etie\tau}=X_{Ftie\tau}\times wgf_{Etie\tau}\ , \quad \text{for } e=\text{agricultural wastes} \tag{6}$$

Conversion level

$$X_{Ctie\tau}=X_{Dtie\tau}\times\eta_{Ctie\tau}, \tag{7}$$

$$X_{Ctie\tau}=\sum_{yr<t,yr<lt} Y_{HC,yr}+Y_{new,t}, \tag{8}$$

Transport/distribution level:

$$\sum_{i}\sum_{\tau}X_{Btije\tau}\times\eta_{Btije\tau}-\sum_{k}\sum_{\tau}X_{Btike\tau}-X_{Atie}=0, \tag{9}$$

End-products:

$$X_{Atie}\ge D_{ti}, \tag{10}$$

$$OC_{lt\tau}=\sum_{i}\sum_{e}co_{ltie\tau}\times X_{ltie\tau}, \tag{11}$$

$$CC_{lt\tau}=\sum_{i}\sum_{e}cc_{ltie\tau}\times Y_{ltie\tau}, \tag{12}$$

$$X\le X_{up}, \tag{13}$$

$$Y\le Y_{up}, \tag{14}$$

$$\cos\ t\le\cos t_{up}. \tag{15}$$

This model integrates the agriculture sector (the resource level) into the industrial technologies to produce biofuel. The potential of land to cultivate different crops in different geographical is considered in Eq. (1) while the limitations on the maximum available lands in each region is described by Eq. (2).

The biomass is available by the wastes or residues. The availability of wastes and residues to produce bio fuel are dependent on variables like the species, harvesting technology, the usage of crops, the harvesting conditions, and efficient crop usage. The harvest residues (lingocellulosic biomass) such as straw, stalk, and leaves may also be used to produce biofuel. The potential of their existence in a specific region are described by Eqs. (3)–(5). The potential of biofuel from the wastes of dedicated available crops

are evaluated by Eq. (6). The method and the coefficients are available by Smeets et al. [3]. The coefficients are *h* the harvest residue generation fraction (i.e. the ratio of the amounts of residues generated to the amount harvested), *hr* the harvest residue recoverability fraction (i.e. the fraction of the harvest residue that can be recovered actually), and *HI* the harvest index (i.e. the ratio of the part of crops harvested to the total crops on the ground). The waste generation fraction is defined as the share of the crops which do not use as food or feed and its quantity is taken from Najafi et al. [18].

The flow and capacity constraints describe the technical limitations of the proposed technologies at the conversion level which are described by Eqs. (7) and (8), respectively. They satisfy the relevant mass balances and determine the new required capacities to be installed in each year in addition to the pervious available capacities in the past. Sugar-based crops contain simple sugars which are easily separated, fermented to raw bioethanol, and purified to obtain the bioethanol fuel. Starch-based crops contain larger carbohydrate molecules. Thus, more pretreatment units are required to be converted to simple sugars through hydrolysis. Then the process is similar to the conversion of sugar-based crops. Cellulosic bioethanol from lingocellulosic biomass needs more processing units than sugar-based and starch-based biomass feedstocks. Physical (milling or chipping) and thermo chemical pretreatments are done before entering the hydrolysis unit. Therefore, the efficiency and the costs of different conversion units will differ by the type of feedstocks. This point is considered in the formulation of conversion level.

The possibility of transportation/distribution of biomass and biofuel within the entire region is provided. The equations are taken from Avami [22] which state that energy carrier from and to each region are equal after considering the efficiency of transport/distribution technology. It is described by Eq. (9). Eq. (10) states that the fuel demand should be satisfied in each region.

The objective function minimizes the annualized operating and capital costs of the whole supply chain which are described by Eqs. (11) and (12). The constraints describe the relations of technologies in different energy levels.

Table 1
Geographical dimension of the model.

Region	Name of relevant states
A	Azarbayjan-e-sharqi, Azarbayjan-e-Gharbi, Ardebil, Gilan, Zanjan
B	Tehran, Qom, Qazvin, Markazi
C	Mazandaran, Golestan, Semnan
D	Khorasan-e-shomali, Khorasan-e- jonubi, Khorasan-e- razavi
E	Kordestan, Kermanshah, Ilam, Lorestan, Hamedan
F	Esfahan, Chaharmahal va Bakhtiary, Yazd
G	Khozestan
H	Fars, Kohkiluyeh va Boyerahmad, Bushehr
I	Hormozgan
J	Kerman, Sistan va Baluchestan

The country is divided into ten regions (nodes) which are listed in Table 1. The application of pipeline and railroad infrastructure to transport biofuels in the country faces serious operational constraints. In this work, trucks transport the biomass and biofuel. The production of BioETBE requires more additional units which are further discussed in Section 3.4.

3. Results and discussion

In order to analyze the main biofuel concerns for decision makers and planners in Iran four scenarios are considered in this work. There are no import and export of the bioethanol and other bio products. Also, the production plants are assumed to be on-farm. The demand for E3 (3 percents of bioethanol are blended with fossil gasoline) is here considered. It is not an easy job to forecast the gasoline consumption in Iran over the next 28 years. The non-optimistic views assume the annual increase of 1 percent. The data information about the agriculture level is available by the agricultural ministry of Iran [23]. The parameters for the conversion level are taken from [24]. The operating cost in the distribution level is available by Energy balance of Iran [25]. Other parameters are taken from Ref. [26]. The amount of maximum land area which is taken from the agricultural ministry is described by Avami [22]. Since the maximum land area is much less than the real cultivated areas in each region, the land management issues are not taken into account in the present work. The fraction of irrigated and rain-fed farms is specified from the historical data reported by the agricultural ministry of Iran [22,23]. The detailed descriptions of different scenarios are given in the following section.

3.1. Biomass wastes (scenario A)

The potential of producing biofuels from the biomass wastes of the present harvested crops is analyzed in this scenario. The waste is defined as the amount of lost crops during different stages between farms and end-user. The waste generation fractions of the level of the supply system are taken from Ref. [18]. The optimal pathway is obtained for the scenario A. The present value of the total cost for E3 is as 2.34E10 $. The optimal results are given in Table 2. The optimal annual land allocation of scenario A (E3 from wastes) is illustrated in Fig. 2. The land area is mainly dominated by date, sugarbeet, and wheat in the early years while the latter years (after 21 years) the wastes of wheat will be the main commercial source of bioethanol production at cultivated areas.

The optimal land areas for different regions are also plotted in Figs. 3–9. Fig. 3 depicts the land areas for corn cultivation to satisfy bioethanol demand (E3) from its wastes. It is mainly cultivated in region C and J in early and later years, respectively. The wastes from date are economically feasible in early years in regions F, E, D, and C (cf. Fig. 4). Barely is mainly cultivated economically in region D which is shown in Fig. 5.

Table 2
Optimal results for different scenarios.

Scenario	Specifications	Operating cost ($)	Capital cost ($)	Bioenergy resources
Scenario A	E3 from wastes	4.75E9	1.87E10	Corn, barley, wheat, sugarcane, sugarbeet, potato, date
Scenario B	E3 from residues	5.93E9	3.79E10	Sugarbeet, date, corn, sugarcane, potato
	E3 from bioenergy crops	4.75E9	2.87E10	Sorghum, switch grass
Scenario C	E3 from wastes, centralized network	4.72E9	9.74E9	Date, potato, wheat, sugarbeet, sugarcane, corn, barley
	E3 from residues, centralized network	5.7E9	2.64E10	Date, sugarbeet, corn, potato, sugarcane, barley
	E3 from bioenergy crops, Centralized network	3.93E9	1.61E10	Sorghum, switch grass, miscanthus
Scenario D	Bio- ETBE from wastes	8.02E9	2.48E10	Corn, barley, wheat, sugarcane, sugarbeet, potato, date
	Bio- ETBE from residues	5.87E9	3.79E10	Sugarbeet, sugarcane, date, corn
	Bio-ETBE from bioenergy crops	6.38E9	3.83E10	Sorghum, switch grass

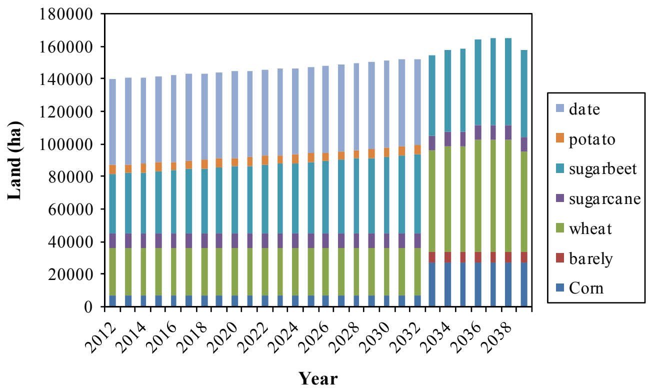

Fig. 2. Optimal land area location from scenario A.

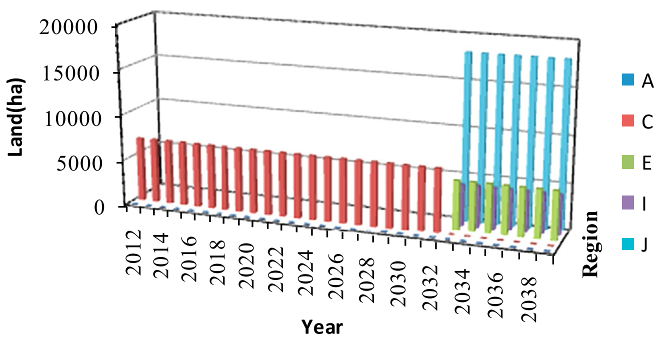

Fig. 3. Optimal land area allocation of corn in different geographical regions from scenario A.

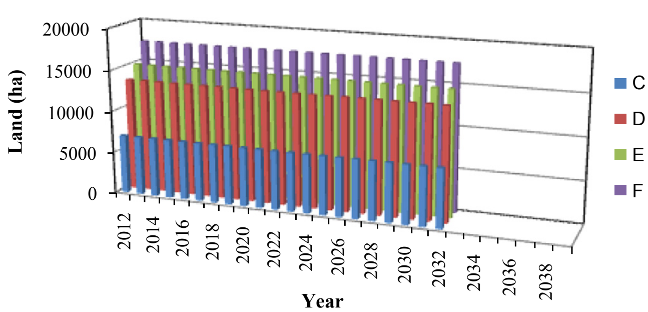

Fig. 4. Optimal land area allocation of date in different geographical regions from scenario A.

Wastes from potato may be commercially used to satisfy E3 in early years especially in region I (cf. Fig. 6). The cultivation of sugarbeet is economically feasible in different geographical regions. However, it is mainly produced in region J in the latter years. It is well depicted in Fig. 7. Sugarcane may be grown in northern or southern parts of Iran as shown in Fig. 8. Based on the techno-economical information, the present study shows that its cultivation in northern parts (region C) is more economical than southern parts (region G). Wheat may be cultivated in different regions but it is mainly grown in region E and J in former and latter years, respectively.

3.2. Biomass residues (scenario B)

The other source of bioethanol production is lingocellulosic materials which are mainly available in crop residues. The abundance and relatively low costs make these feedstocks as attractive options to sufficiently produce biofuels [27,28]. Thus, in this

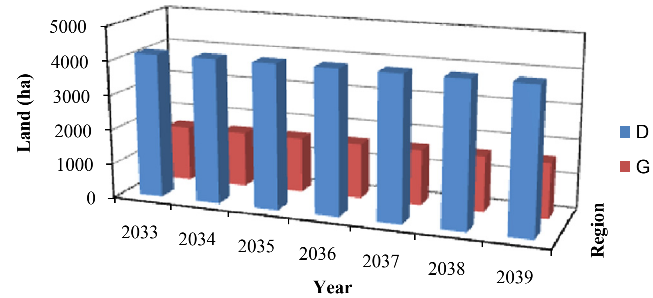

Fig. 5. Optimal land area allocation of barely in different geographical regions from scenario A.

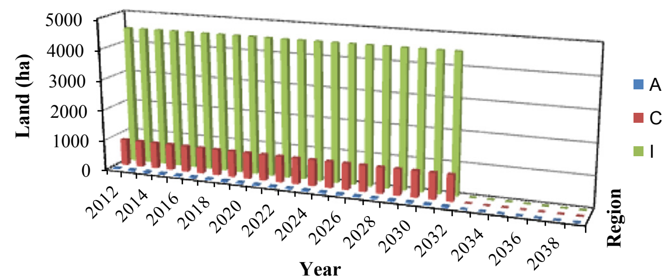

Fig. 6. Optimal land area allocation of potato in different geographical regions from scenario A.

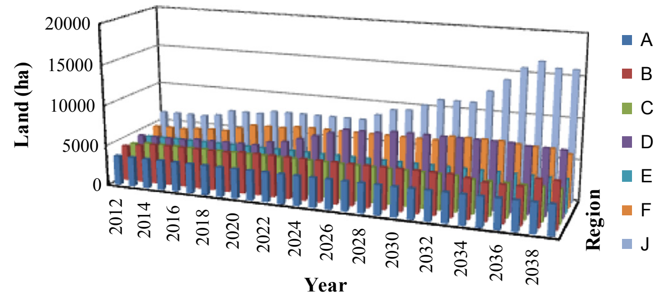

Fig. 7. Optimal land area allocation of sugarbeet in different geographical regions from scenario A.

scenario the production potential of the residues from the present cultivated agricultural crops in Iran is considered firstly. These crops are corn, barely, rice, wheat, sugarcane, sugarbeet, potato, and date. Due to the soil degradation and decreasing its organic matter, some parts of crop residue should be left in the fields. This amount will differ depending on the weather and soil conditions, crop rotation, etc. Here, the available residues are estimated by the method, expressed by Eqs. (3)–(5), proposed by Smeets et al. [3]. Taken into account the whole supply chain from agriculture, harvesting, collecting, conversion processes, and distribution systems, the model is executed by the assumptions in the current scenario. The total present cost of the system is 4.38E10 $, as described in Table 2. As it is depicted in Fig. 10, the residues from sugarbeet are prevailing resource. However, in later years corn may contribute economically to produce bioethanol. The contribution of other crop residues is not too much or economical.

The bio energy fast growing crops which may be grown in the Iranian weather and geographical conditions are here considered secondly. These crops are sorghum, miscanthus, and switch grass. Since there is not any reliable estimation about the harvesting cost of these crops in the country, they are taken from Ref. [29]. This information is considered the same throughout the whole cultivated geographical regions. The total present cost of the system is

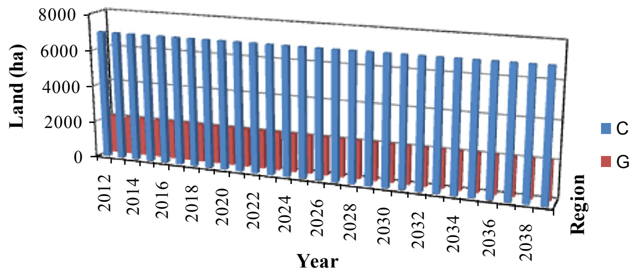

Fig. 8. Optimal land area allocation of sugarcane in different geographical regions from scenario A.

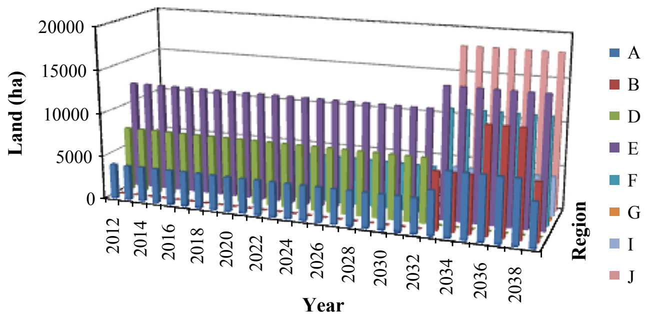

Fig. 9. Optimal land area allocation of wheat in different geographical regions from scenario A.

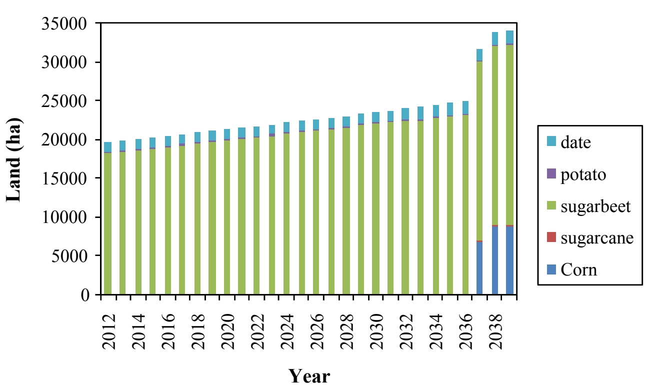

Fig. 10. Optimal land area allocation from agricultural residues in scenario B.

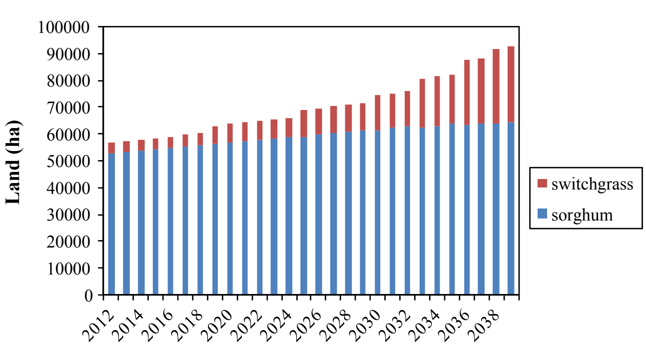

Fig. 11. Optimal land area allocation from bioenergy crops in scenario B.

3.34E10 $ (Table 2). The optimal land areas are illustrated in Fig. 11. The main bioenergy crops are determined as sorghum and partially switch grass. Miscanthus is not economically feasible to be grown for biofuel.

3.3. Centralized production system (scenario C)

The centralized production systems are defined such that the biorefinery plants are located where the end users demand the fuel. Thus, it reduces the cost of distributing network while the flexibility of the supply chain and the security of the demand satisfaction are lowered. In this scenario, the centralized bioethanol production from waste, residues, and bioenergy crops are investigated. The total costs of the whole supply chain are 1.45E10 $, 3.21E10 $, and 2E10 $ for agricultural wastes and residues and bioenergy crops, respectively. Fig. 12 illustrates the amount of land needed to satisfy the E3 demand from agriculture wastes. Date and wheat are two main biomass feedstocks. Date residues are the prevailing biomass to centralized production of bioethanol as it is shown in Fig. 13. Fig. 14 depicts the land areas to grow the bioenergy crops. Again, sorghum contributes significantly to meet

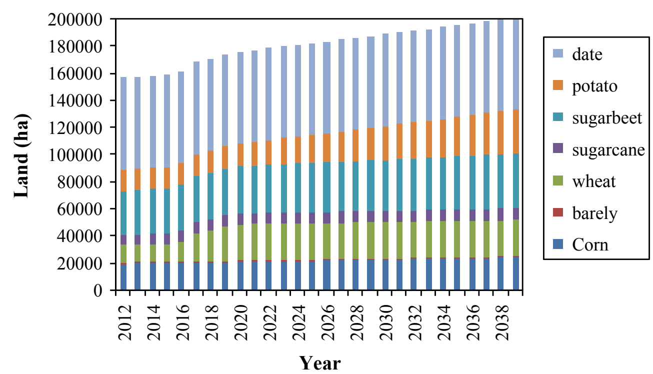

Fig. 12. Optimal land area allocation from agricultural wastes in scenario C.

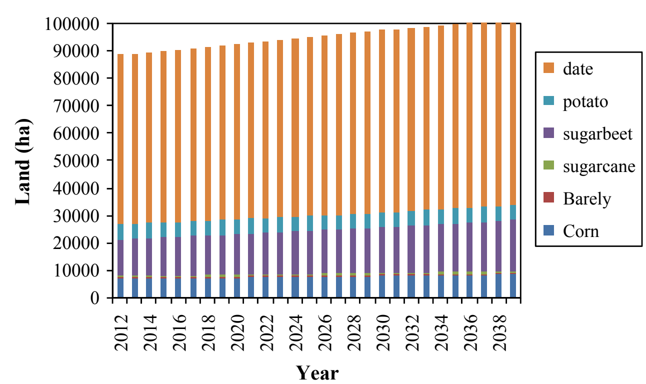

Fig. 13. Optimal land area allocation from agricultural residues in scenario C.

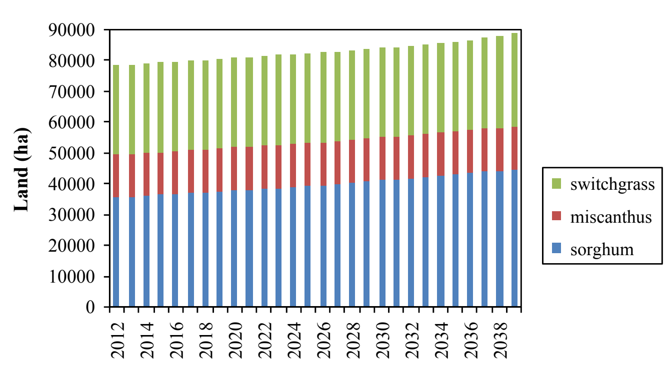

Fig. 14. Optimal land area allocation from bioenergy crops in scenario C.

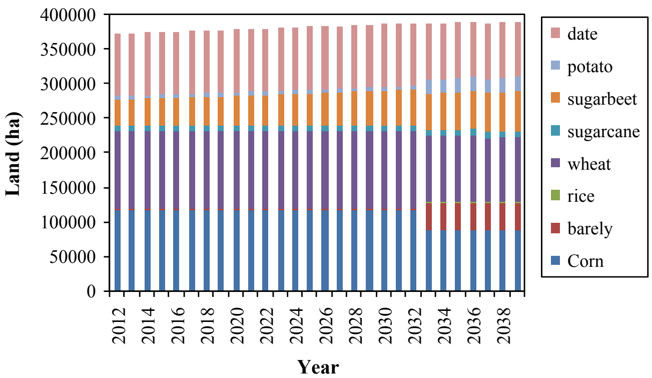

Fig. 15. Optimal land area allocation to produce ETBE from agriculture wastes in scenario D.

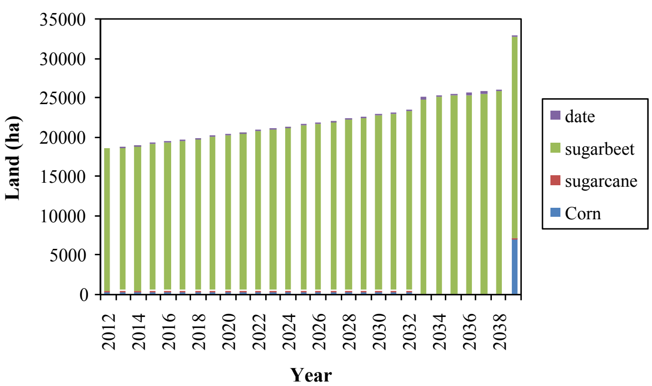

Fig. 16. Optimal land area allocation to produce ETBE from agriculture residues in scenario D.

the demand. However, miscanthus is economically feasible for the centralized production considering the geographical potential of cultivation.

3.4. ETBE production (scenario D)

Bioethanol is used directly as a mixture with gasoline as an automotive fuel (Scenarios A and B) and may be converted to bio-ETBE as a fuel additive (scenario D). Bio-ETBE is commercially produced by the chemical reaction of bioethanol and iso-butylene in the presence of heat over a suitable catalyst. In this scenario, it is planned to replace 8 percent (vol) of gasoline with ETBE. The conversion information is taken from Refs. [30,31]. The present costs of the whole system are 3.28E10 $, 4.38E10 $, and 4.46E10 $ for wastes, residues, and energy crops, respectively. Figs. 15–17 describe the land allocation information among different biomass feed stocks from wastes, residues, and bioenergy crops, respectively. Based on the present techno-economical database, the model selects corn, wheat, and date as three main resources to produce BioETBE from wastes. Sugarbeet is the prevailing resource for the lingocellulosic biomass. Sorghum is the most interesting bioenergy crop to meet the BioETBE demand.

4. Conclusion

The present study introduces an analytical tool to evaluate bioethanol supply chain in Iran. The model shows that centralized production from bioenergy crops and wastes are two most economical pathways. However, the production costs from residues may be lowered by the introducing new technological ways.

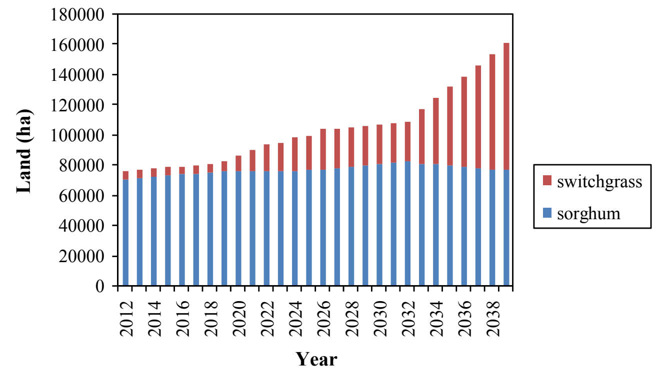

Fig. 17. Optimal land area allocation to produce ETBE from bioenergy crops in scenario D.

BioETBE may be successfully produced to cover the demand from the current potentials in Iran during the next decades. Therefore, significant attention is required to commercially produce this additive. However, other strategic consideration such as increasing demand of gasoline and additives approves the necessities of biofuel production and confirm the results obtained from the present work. In order to analyze bioenergy production in Iran comprehensively, the supply chain may be developed to include all routes of biorefineries. In this way, the optimal paths to reach a sustainable bioenergy system will be investigated in future works. In this way the competitiveness of these renewables with the alternative current fuels and their diffusion into the whole energy supply chain are analyzed in depth.

Disclaimer

This model in the present work is only used for research purposes. For specific applications please contact the author regarding the scope of the model.

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